

# Phases of Dense Quark Matter and The Structure of Compact Objects

Andrew W. Steiner

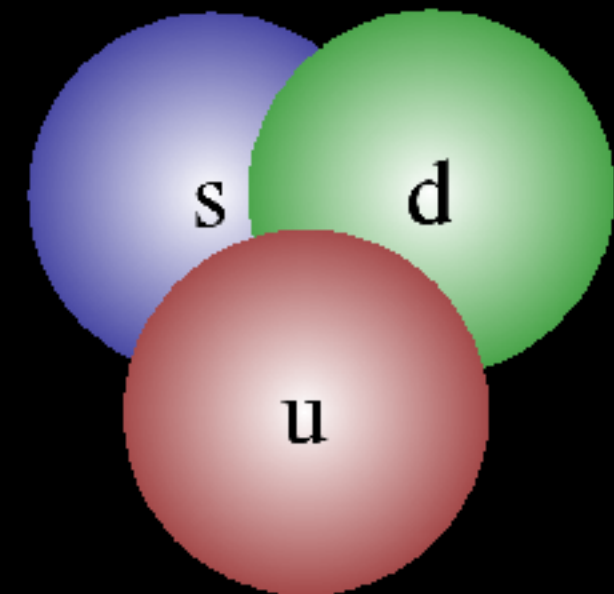
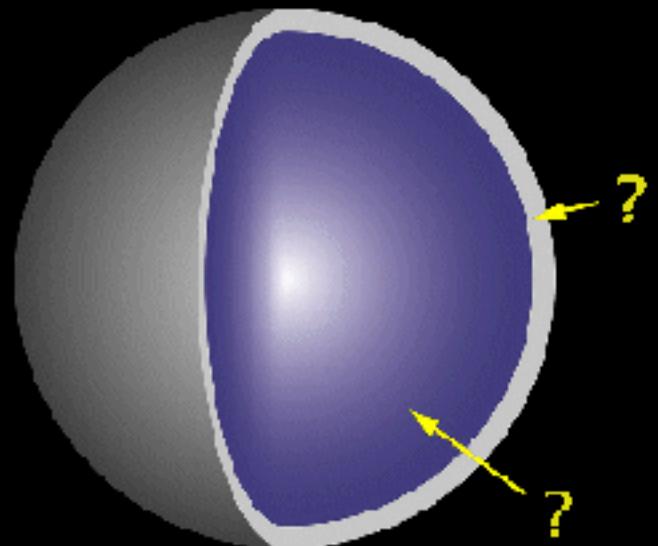


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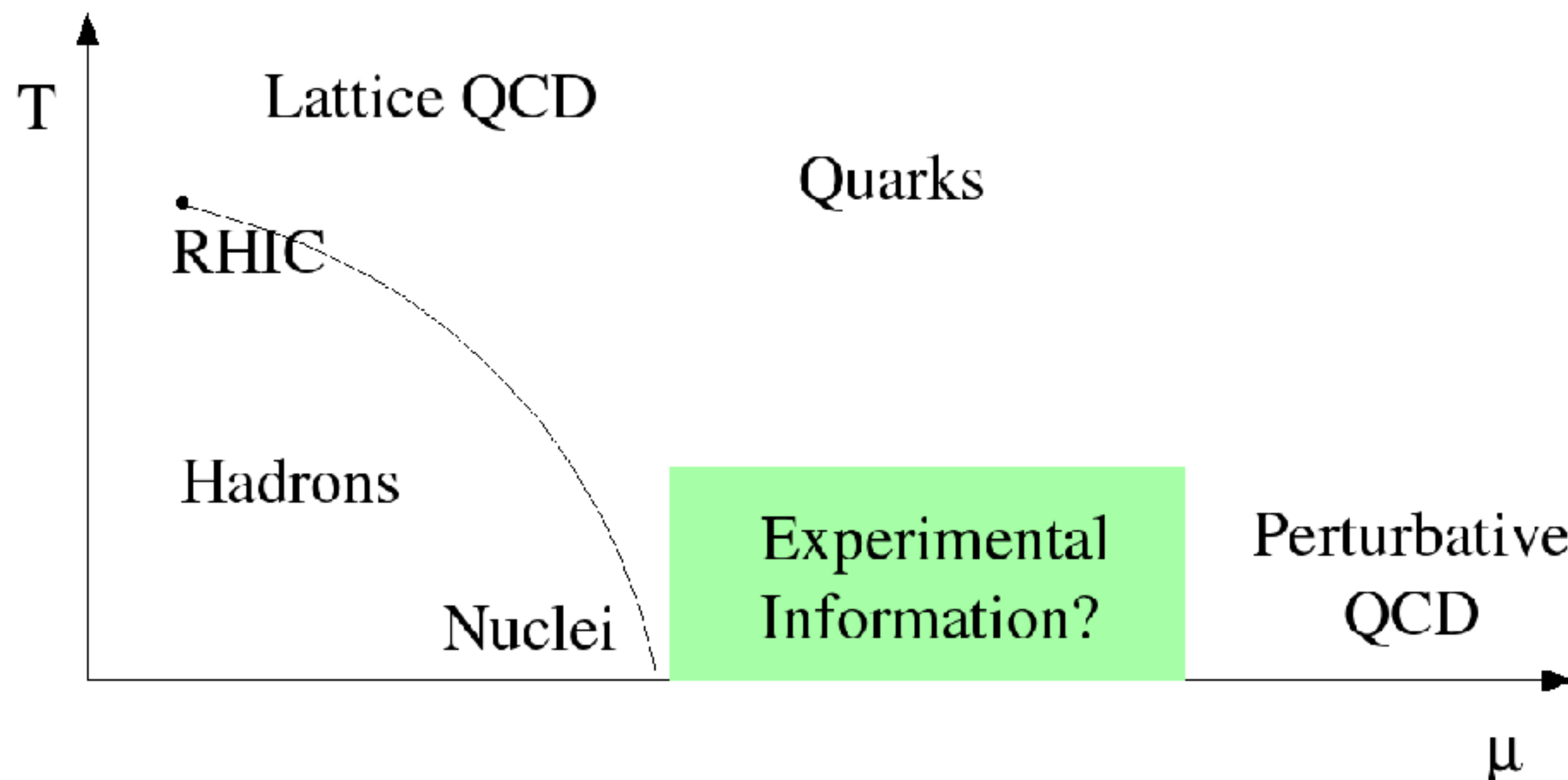
Collaborators: M. Alford (Wash. U. St. Louis),  
P. Jaikumar (Argonne), K. Rajagopal (MIT), S. Reddy (LANL)

Neutron star



# Why study quark matter in neutron stars?

- The ground state of matter at sufficiently large density must consist of deconfined quarks. [Itoh \(1970\)](#), [Bodmer \(1971\)](#), [Collins and Perry \(1975\)](#), [Baym and Chin \(1976\)](#), [Freedman and McLerran \(1978\)](#)
- The critical density of the "deconfinement" phase transition is not well known - but could very well be lower than the central density of neutron stars
- The confirmation of the existence of quark matter in neutron stars would:
  - Provide an important observational constraint on the nature of QCD at low temperatures and finite density.
  - Provide important input for the description of neutron stars



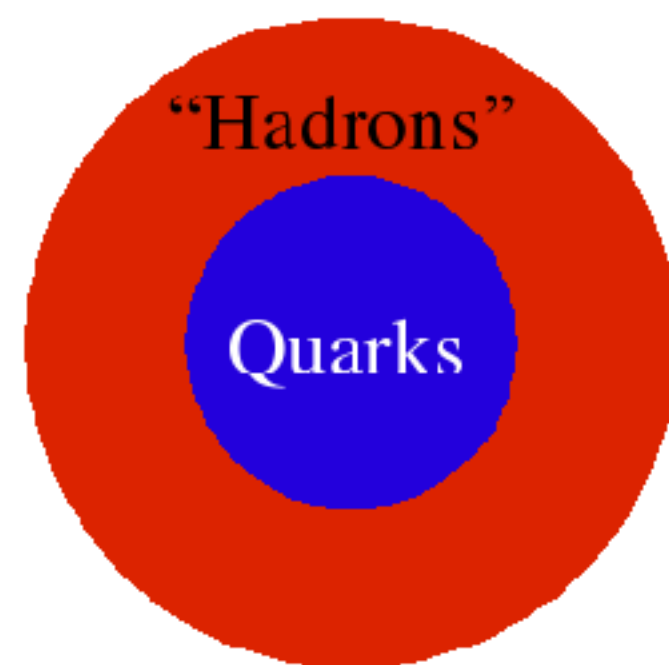
# Outline

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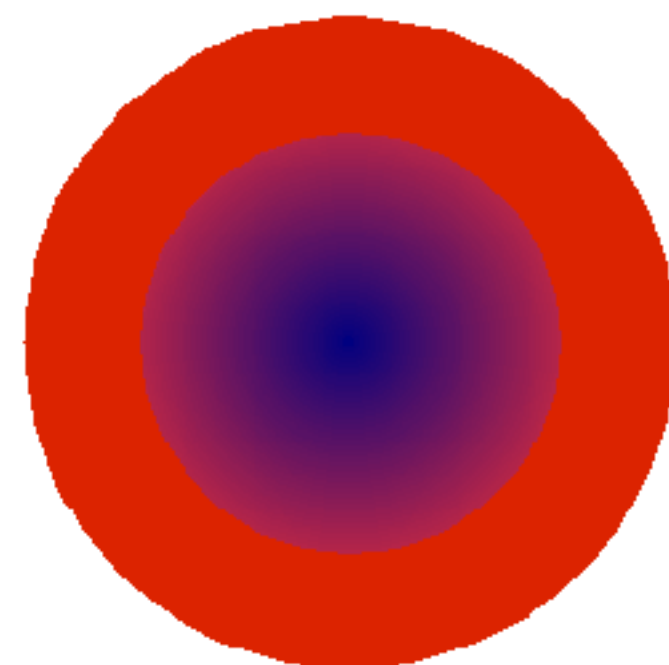
- . Phenomenology
- . Color Superconductivity
- . Color Superconducting 't Hooft Interaction
- . Strange Crusts for Strange Stars
- . Summary

# Phenomenology

- There are (loosely) four kinds of neutron stars containing quark matter
- Hybrid stars exist only on the assumption that the central density of a neutron star is large enough that quarks become deconfined
- "Bare strange quark stars" require the additional assumption that strange quark matter is absolutely stable (Energy/baryon less than 931 MeV = mass of Fe)
- Strange quark stars may have a crust of hadronic matter.



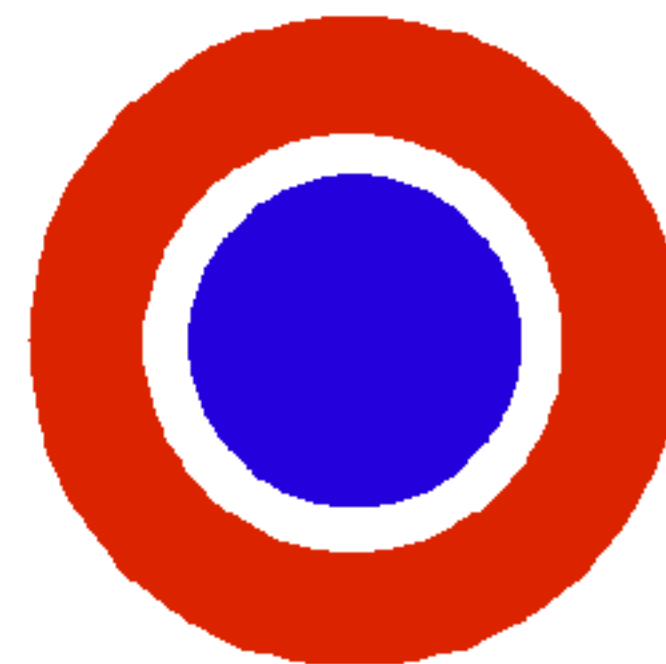
Hybrid Neutron Star  
(large surface tension)



Hybrid Neutron Star  
(zero surface tension)



Bare strange quark  
star



Bare strange quark  
star (with crust)



# Color Superconductivity

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- A one-component system of fermions with a net attractive interaction has a ground state which is unstable with respect to the formation of Cooper pairs.
- One-gluon exchange is attractive in the 3-bar channel - the ground state is antisymmetric in color, flavor and spin. Furthermore, the ground state has the structure:

$$\varepsilon^{ijk} \varepsilon^{\alpha\beta\gamma}$$

This is color-flavor-locking (CFL).

[Bailin and Love \(1984\)](#), [Alford, Rajagopal, and Wilczek \(1998\)](#), [Rapp, et. al \(1998\)](#)

- Naively, we expect pairing when the Fermi surfaces are close - this is frequently the case and nearly all quark matter in neutron stars contains pairs of some type.
- The strange quark mass may be sufficiently large - The 2SC phase.
- Color-neutrality - homogeneous quark matter should be color-neutral. This implies that the CFL phase is electrically neutral without electrons.  
[Alford and Rajagopal \(2002\)](#), [Steiner, Reddy, and Prakash \(2002\)](#)
- Additional "stresses" on the system may decrease the gap or favor unpaired states

# Model Description of Quark Matter

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- NJL models - The high-energy degrees of freedom (gluons) are integrated out  
[Nambu and Jona-Lasinio \(1961\)](#)

- Dirac term:

$$\bar{\psi}(i\partial - m)\psi$$

- Quark-anti-quark four-fermion interaction:

$G(\bar{\psi}\psi)(\bar{\psi}\psi)$  - provides spontaneous breaking of chiral symmetry

- Quark-quark four-fermion interaction:

$G_{\text{DIQ}}(\bar{\psi}\psi_c)(\bar{\psi}_c\psi)$  - gives color-superconductivity (CFL, 2SC, gapless, LOFF)

- Quark-anti-quark six-fermion interaction:

$K(\bar{\psi}\psi)(\bar{\psi}\psi)(\bar{\psi}\psi)$  - Breaks axial U(1)

['t Hooft \(1986\)](#)

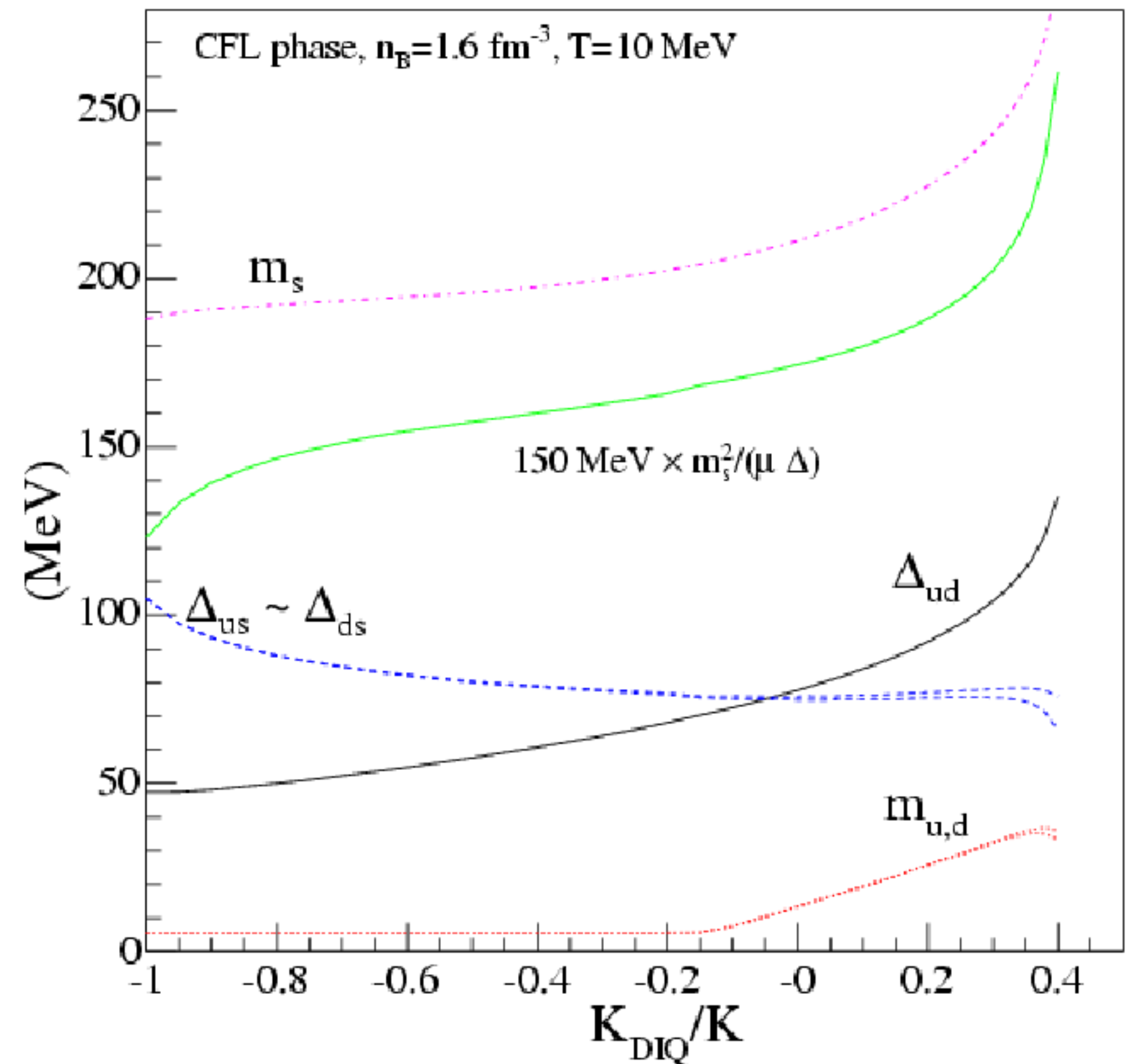
- Quark-quark six-fermion interaction:

$K_{\text{DIQ}}(\bar{\psi}\psi_c)(\bar{\psi}_c\psi)(\bar{\psi}\psi)$  - Further modifications to the quark masses and gaps -  
Novel breaking of chiral symmetry

[Rapp et. al. \(1998\)](#), [Schaefer \(2002\)](#), [Steiner \(2005\)](#)

# Color Superconducting 't Hooft Interaction

- Denote the unknown coupling constant by  $K_{\text{DIQ}}$ . Vary  $K_{\text{DIQ}}/K$  between -1 and 1.
- The strange quark mass can be modified by 50 percent, and the gaps are modified by a factor of two.
- The CFL phase is not present for sufficient large values of  $K_{\text{DIQ}}$ .
- The value of  $K_{\text{DIQ}}$  can significantly modify the phase structure.



Steiner (2005)



# Bare Strange Quark Star Crusts

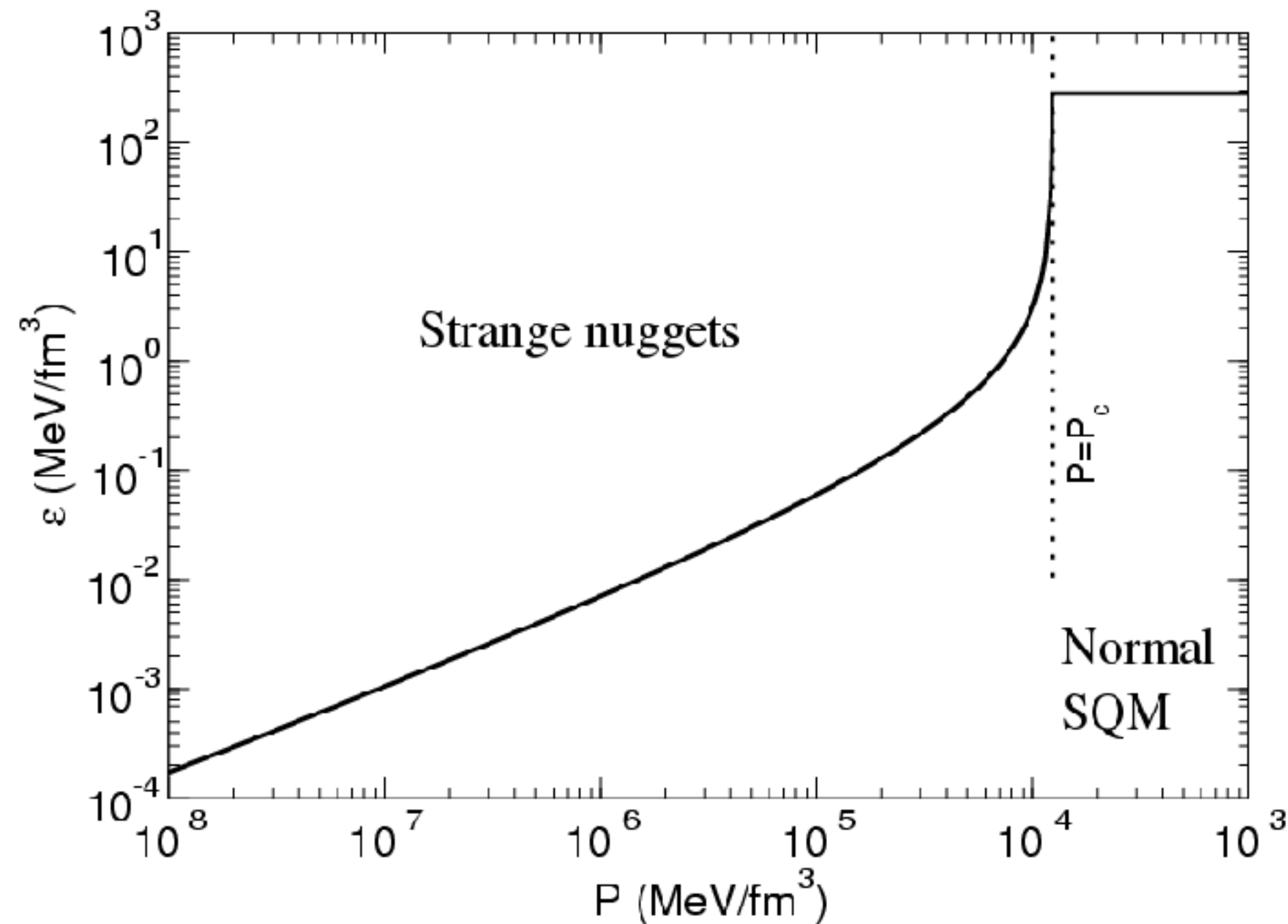
- If strange quark matter is stable then some neutron stars may be strange quark stars

Bodmer (1971), Witten (1984)

- Strange quarks stars can have strange crusts

Haensel, Zdunik and Schaeffer (1986),  
Jaikumar, Reddy, and Steiner (2005)

- Crust consists of droplets of quark matter immersed in a sea of degenerate electrons



Jaikumar, Reddy, and Steiner (2005)

- The strange crust will give a small thermal conductivity and can thus support a large temperature gradient
- Neutrino opacities will be increased by the droplets



# Summary

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- . Neutron stars are an ideal laboratory for QCD in regions of the phase diagram which are otherwise unobservable.
- . It is not at all unlikely that we could confirm or rule out the presence of quark matter in neutron stars in the near future.
- . For this reason, it is important to try to fully understand the nature of dense quark matter.
- . The color-superconducting t'Hooft interaction can qualitatively modify the nature of dense matter.
- . Strange quark stars may have strange crusts. These crusts can change the evolution of strange quark stars.